

STRUCTURAL ASSESSMENT OF A NOVEL  
CARPET COMPOSITE MATERIAL

By

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COMPOSITE MATERIAL

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**Abstract:** Noise pollution caused by vehicles has always been a concern to the communities in the vicinity of highways and busy roadways. The carpet composite material was recently developed and proposed to be utilized as sound-walls in highways. In the carpet composite material post-consumer carpet is used as reinforcing element inside and epoxy matrix. The main focus of this work is to assess flexural behavior of this novel material. Tests were performed on the individual components of the composite material. Using the results from the test and a theoretical approach, a model was proposed that describes the flexural behavior and also a close estimate of the flexural strength of the carpet composite material. In this work the contribution of the carpet in flexural behavior of the composite material was investigated. It was found that the carpet is weaker than the epoxy and the contribution of the carpet in flexural strength of the composite material is small. It was also found that using the carpet inside the epoxy results in 63% decrease in ultimate strength of the section, however; the gain in ductility is considerable. Based on the flexural test results the composite section follows a bilinear behavior. To determine the capacity of the composite, the effective epoxy section is to be determined before and after the tension cracks form at the bottom of the section. Using the epoxy section analysis described in this work, the strength of the composite section can be calculated at cracking and ultimate capacity.

## Table of Contents

Chapter	Page
I: INTRODUCTION .....	1
1.1 Overview .....	1
II: ANALYSIS OF THE CARPET COMPOSITE MATERIAL BEHAVIOR .....	2
2.1 Introduction .....	2
2.2 Methodology .....	6
2.2.1 Compression test on epoxy cylinders .....	6
2.2.2 Three points flexural test on the epoxy and carpet composite samples .....	7
2.2.3 Tension Test on the Carpet .....	10
2.3 Results .....	14
2.3.1 Epoxy and composite samples in flexure .....	14
2.3.2 Epoxy in Compression .....	15
2.3.3 Carpet in tension .....	16
2.4 Discussion .....	17
2.4.1 Epoxy in flexure .....	17
2.4.2 The carpet composite in flexure .....	24
2.4.3 Contribution of the carpet in flexural behavior of the composite material .....	25
2.4.4 Bilinear behavior of the composite in flexure .....	25
2.4.5 Proposed model for carpet composite in flexure .....	26
2.4.6 Summary of the method .....	31
2.4.7 Conclusion .....	32
III: FUTURE WORKS AND RECOMMENDATIONS .....	34
3.1 Overview .....	34
3.2 Restrictions on application of the results of this study .....	34
3.2.1 Non-Uniform Density .....	35
3.2.2 Different Carpets: .....	36
3.3 Future works and recommendations .....	38
REFERENCES .....	39

STANDARDS .....	40
APPENDECES .....	41
A.1 Estimating flexural capacity for rectangular epoxy sections .....	41
A.2 Estimating flexural capacity for nonrectangular epoxy sections .....	44

### **List of Tables**

Table 2-1: dimensions for epoxy cylinders for compression test. ....	7
Table 2-2: epoxy properties based on three points flexural test .....	23
Table 3-1: density of different composite sample.....	36

## List of Figures

Figure 2-1: VARTM final setup .....	4
Figure 2-2: side view of a finished carpet composite sample .....	4
Figure 2-3: composite sample cross section .....	5
Figure 2-4a: epoxy cylinder sample for compression test Figure 2-4b: compression test setup .....	7
Figure 2-5: MTS 810 testing machine .....	8
Figure 2-6: typical sample for three point flexural test.....	8
Figure 2-7: Epoxy sample in three points flexural test setup.....	9
Figure 2-8: General layout of carpet specimens for tension test .....	11
Figure 2-9: The grips used for carpet tension test.....	11
Figure 2-10: carpet section view .....	12
Figure 2-11: carpet sample in tension test .....	13
Figure 2-12: Moment vs. Deflection diagram of the epoxy and the composite in flexure	14
Figure 2-13: stress-strain plateau of epoxy under axial load .....	15
Figure 2-14: Load-Displacement diagram for carpet sample in tension.....	16
Figure 2-15: transformed cross section of the epoxy in flexure .....	18
Figure 2-16: stress diagram over the transformed epoxy cross-section.....	19
Figure 2-17: large air voids in the carpet backing areas .....	27
Figure 2-18: buckling of the top layer in a failed sample .....	27
Figure 2-19: Effective cross section of the composite at cracking and ultimate flexural strength.....	28
Figure 3-1: section view of two samples from two different sheets .....	35
Figure 3-2: cross section view of different samples .....	36
Figure 3-3: top view of the new and old carpet backing inside the composite sample ....	37
Figure A-1: epoxy section with stress and strain diagram.....	41
Figure A-2: transformed cross-section of the 0.7” deep epoxy .....	42
Figure A-3 nonrectangular epoxy cross-section .....	44

# **CHAPTER I**

## **INTRODUCTION**

### **1.1 Overview**

A new composite material has recently been proposed to be used as sound barrier walls along the highways. Sound walls are designed to diminish the amount noise transferred from highways to nearby residential and commercial areas. The new composite product consists of epoxy matrix and recycled carpet. The main purpose of this work is to determine the mechanical behavior of the new composite material.

The flexural behavior of the composite material is of main concern in this research. In order to evaluate the composite material properly, two components of the composite are tested in different loading conditions to be assessed individually. Pure epoxy is tested in both compression and flexure. The tensile properties of the epoxy are derived accordingly. Also the raw carpet is tested in tension. Finally the composite material is tested in flexure. The details about each test are explained in methodology section. Performing these tests helps develop a preliminary analytical model to better describing the behavior of the epoxy being reinforced by carpet as new composite material.

In this work an attempt is made to theoretically estimate the flexural capacity of the composite material for future applications and to provide analogous information for comparing the strength of the new material with conventional materials used as sound barriers.



## **CHAPTER II**

### **ANALYSIS OF THE CARPET COMPOSITE MATERIAL BEHAVIOR**

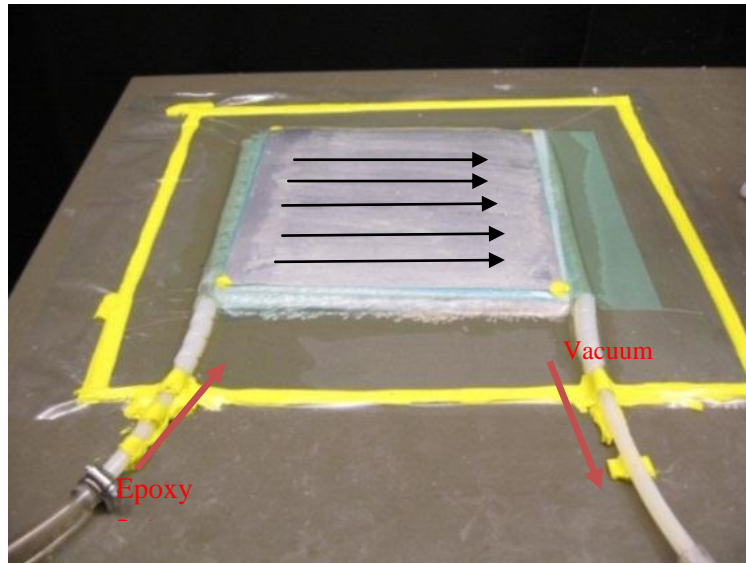
#### **2.1 Introduction**

Noise pollution caused by cars has always been a great concern in populated metro areas. This problem becomes more unpleasant for habitants of areas in vicinity of busy highways with vehicles traveling at high speed. Ohio Turnpike Commission started a Noise Mitigation Study on 2008 to investigate different methods to reduce the noise in areas neighboring the highways. The project was awarded to TranSystem of Cleveland in which the different factors that help dissipate the noise generated in the highways have been examined. Examining new configuration for sound walls, investigating new pavements that reduce the noise caused due to tire/pavement interaction and comparing innovative materials with traditional materials that used as sound walls are some parts of this ongoing project (TranSystem 2008).

In the same regard, OKTC (Oklahoma Transportation Center) supported a project in which a new composite material was proposed using recycled carpets to be used as highway sound barriers (Vaidyanathan 2011). In this innovative material the post-consumer carpet is to be used in an epoxy medium to create a new composite material that could be proposed as an alternative to traditional materials used as sound walls. Recent research has been performed on the fabrication of the recycled carpet composite material (Lakshminayaranan 2011). Also noise blocking performance and other material properties were evaluated in this work.

Classic composites in general consist of two principal components with unique physical or chemical properties. One is reinforcing element and the other one is the medium which is also known as the matrix. The two components provide complementary properties to improve the desired properties in a form of new material. Reinforced concrete for instance is a classic composite material that is widely used in variety of structures. Concrete has high compressive strength but it is weak in tension. Steel reinforcement however, makes up for the concrete weakness in tension. Combining concrete with steel provides a material that is strong in both tension and compression. This is the basic concept behind the invention of new composite materials.

The carpet composite is a mixture of commercially available epoxy (System 2000) and epoxy hardener (system 2120) produced by Fiber Glast Development Corporation. But unlike traditional composite materials in which high strength fibers are used as reinforcement for the epoxy, carpet and backing material is used as reinforcing fibers. The carpet composite material was prepared with techniques outlined by Lakshminarayanan (2011). The VARTM (Vacuum Assisted Resin Transfer Molding) method is used to fabricate this composite material. In VARTM method, epoxy is fed to the carpet by vacuuming the epoxy through the carpet placed in a sealed bag. Fig. 2-1 is a general demonstration of the procedure.

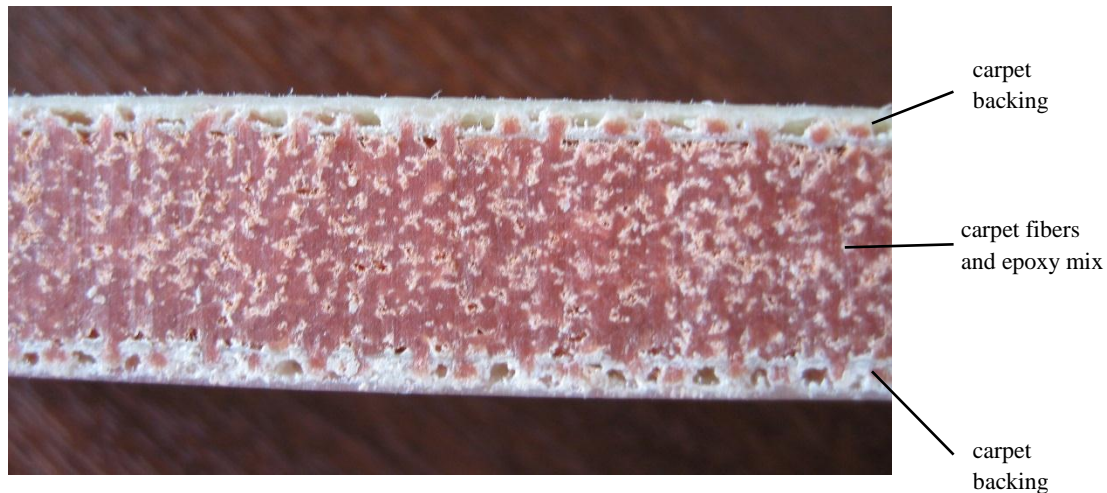


**Figure 2-1: VARTM final setup**  
the arrows show the direction in which the epoxy is sucked through the carpet toward the vacuum.

The hardener used for curing the epoxy requires two hours of set time. Originally the samples would be cured for 24 hours in room temperature (73° F). However, occasionally some samples were found not fully cured on the surface. Therefore, it was decided to post-cure the samples for another 6 hours in 120° F. The samples were made in larger sheets and then saw cut to desired sizes for different tests. Fig. 2-2 shows side view of the finished specimens prepared for flexural test while fig. 2-3 illustrates the closer view of the cross section of the composite sample with different consisting layers.



**Figure 2-2: side view of a finished carpet composite sample**



**Figure 2-3: composite sample cross section**

Lakshminarayanan (2011) performs an impedance tube test (ASTM 384-04) in which the results suggest that the coefficient of noise absorption is some 4.3 times higher for the carpet composite material compared to normal concrete. However, since this material is to be used as sound walls, one key concern about the new material is the structural performance. The primary load that will be applied to this material is wind load as sound walls have a large area. Therefore, the carpet composite material should primarily be subjected to flexure. This has been the main focus of this research.

Kebede (2011) conducted four points and three points flexural tests on the carpet composite material prototypes. The results show that the average overall flexural modulus of the carpet composite material is approximately 221.8 KSI for tested samples. The research provides general flexural capacity of the composite samples; however does not provide any analytical model for it.

It should be mentioned that the manufacturing process for the composite material was evolving as this work was being done. It was not uncommon to receive samples with different thickness, air volume and consequently different densities. Therefore, results will be presented in normalized values such as stress. Also, the data used for analysis purpose is from the tests that

were performed on samples that were all extracted from a single large sample with the same properties throughout the sample. More information about the non-uniformity of the samples is provided in chapter 3.

It is the goal of this study to provide more information about the mechanical behavior of these novel materials and derive analytical model that explain their performance. To achieve this, laboratory tests were completed and equations were developed that can aid the design of these materials. This study will be helpful to the adoption of these materials for engineering applications such as sound walls.

## **2.2 Methodology**

Tests were completed on the individual components of the composite material so that the behavior could be better predicted. The testing machine recorded the load and deflection of the material at every stage of the test. In addition to testing composite samples in flexure, epoxy samples were made and tested in three points flexural test setup. Also epoxy cylinders were tested in compression and finally the raw carpet was tested in tension.

### **2.2.1 Compression test on epoxy cylinders**

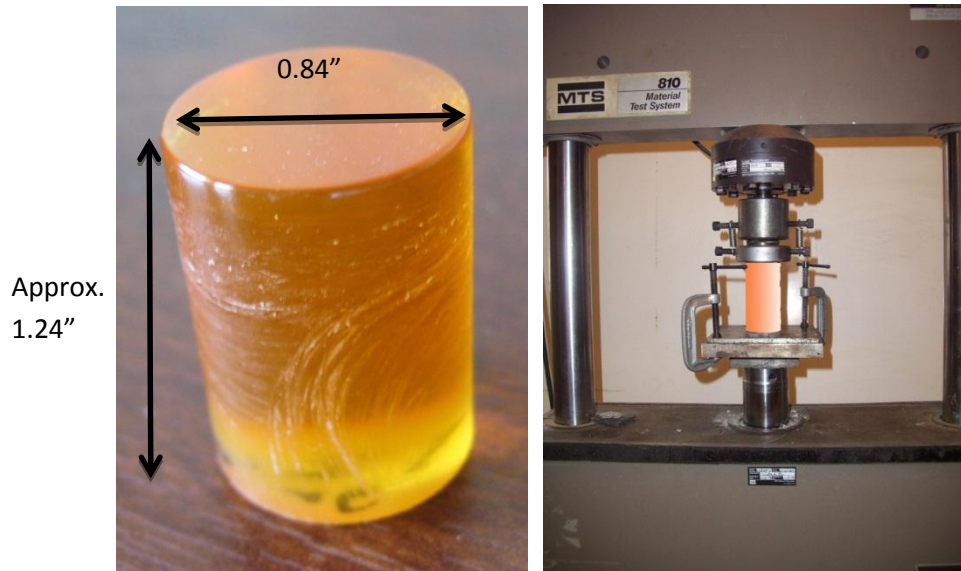
Three compression tests were performed on cylindrical epoxy samples to determine the strength and modulus of elasticity in pure compression. Cylinders were made according to the procedure provided by the manufacturer. The epoxy and hardener are mixed with the weight ratio of 100:27 respectively. The samples then will be cured in room temperature (73° F) for 24 hours and will be post cured in oven at 120° F for 6 hours. The MTS-810 machine automatically records the load and deflection of the material each second.

The compression tests are performed based on ASTM-D659-10 (Standard Test Method for Compressive Properties of Rigid Plastics). Table 2-1 shows the dimensions of the samples.

**Table 2-1: dimensions for epoxy cylinders for compression test**

Sample#	Height(in)	Diameter(in)
1	1.245	0.84
2	1.252	0.84
3	1.23	0.84

The rate of loading is approximately 0.04 in/min, which is within the given value in ASTM-D659. Fig. 2-4a shows a typical epoxy cylinder specimen and fig. 2-4b illustrates the general configuration of the compression test.

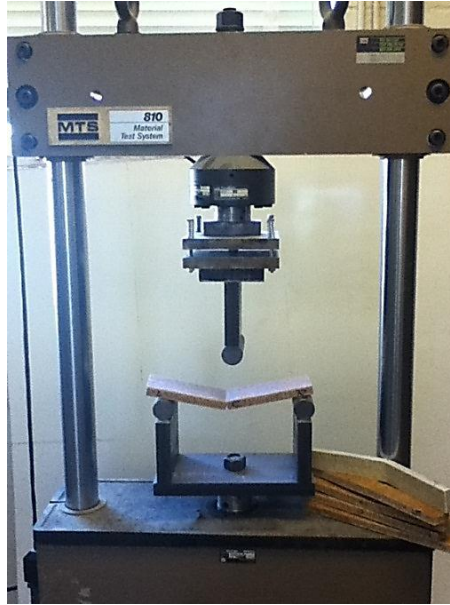


**Figure 2-4a: on the left: epoxy cylinder sample for compression test**  
**Figure 2-4b: on the right: compression test setup**

### **2.2.2 Three points flexural test on the epoxy and carpet composite samples**

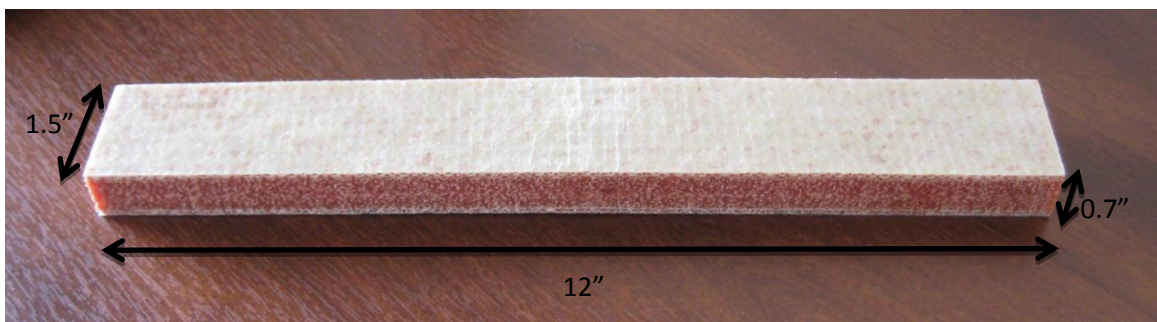
Flexural tests were performed on the carpet composite samples to determine its flexural strength and to compare them with the flexural strength of samples made only of epoxy. As shown in fig. 2-5, a simply supported boundary condition is provided with a point load applied at the mid-span. The tests are performed in accordance with ASTM-D790-10 (Standard Test

Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials) as it is the closest standard test for the given composite material.



**Figure 2-5: MTS 810 testing machine**

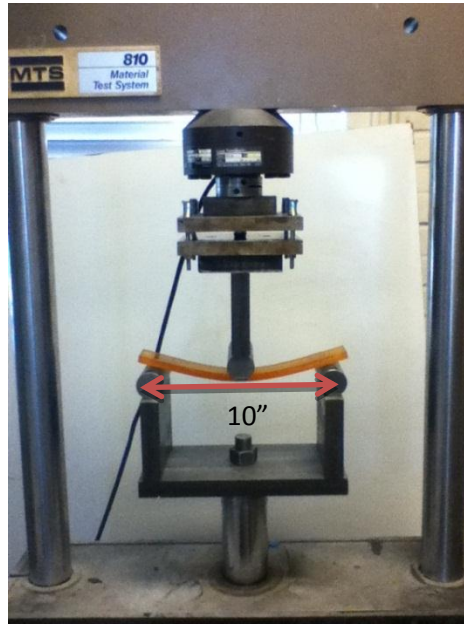
ASTM-D790 suggests an aspect ratio of 16 for span length to depth for the three point flexural test. Due to variability in the sample depth and the requirements to use a fixed frame, a 10" long span is used for the flexural test. This provides a span to depth ratio of approximately 14.3. For each side of the samples an inch of overhang is considered to avoid slippage of the samples on the supports. Fig. 2-6 shows a typical sample with the dimensions that is prepared for flexural test.



**Figure 2-6: typical sample for three point flexural test**



The same test also was performed on three epoxy samples. Epoxy samples were 12” long, 1.5” wide and approximately 0.5” deep. Fig. 2-7 shows an epoxy sample in the three point flexural test setup. Epoxy samples were made according to the manufacturer’s procedure as described in [2.2.1]



**Figure 2-7: Epoxy sample in three points flexural test setup**

Usually, flexural tests performed on plastics and epoxies are displacement controlled tests rather than force controlled. ASTM-D790 as well, suggests a strain based formula for the rate of crosshead motion as follows:

$$R = \frac{ZL^2}{6d} \quad (2-1)$$

Where:

R = rate of crosshead motion, mm (in.)/min

L = support span, mm (in.)

d = depth of beam, mm (in.)

Z = rate of straining of the outer fiber, mm/mm/min (in./in./min). Z shall be equal to 0.01.

According to eqn. 2-1 the rate of cross head movement is found to be 0.3 in/min.



Originally, the average thickness of received composite samples was about 0.5". Later as the material evolved and a new carpet was used in the composite samples the average thickness increased to 0.7". Epoxy samples were dimensioned to match the dimensions of original composite samples. Therefore, since the depth of epoxy samples tested in the laboratory did not match the composite samples anymore, in order to make comparable data, the expected moment-deflection diagram of the epoxy samples of the same depth as the composite samples (0.7" deep) were calculated and shown in result section based on section analysis provided in the discussion section.

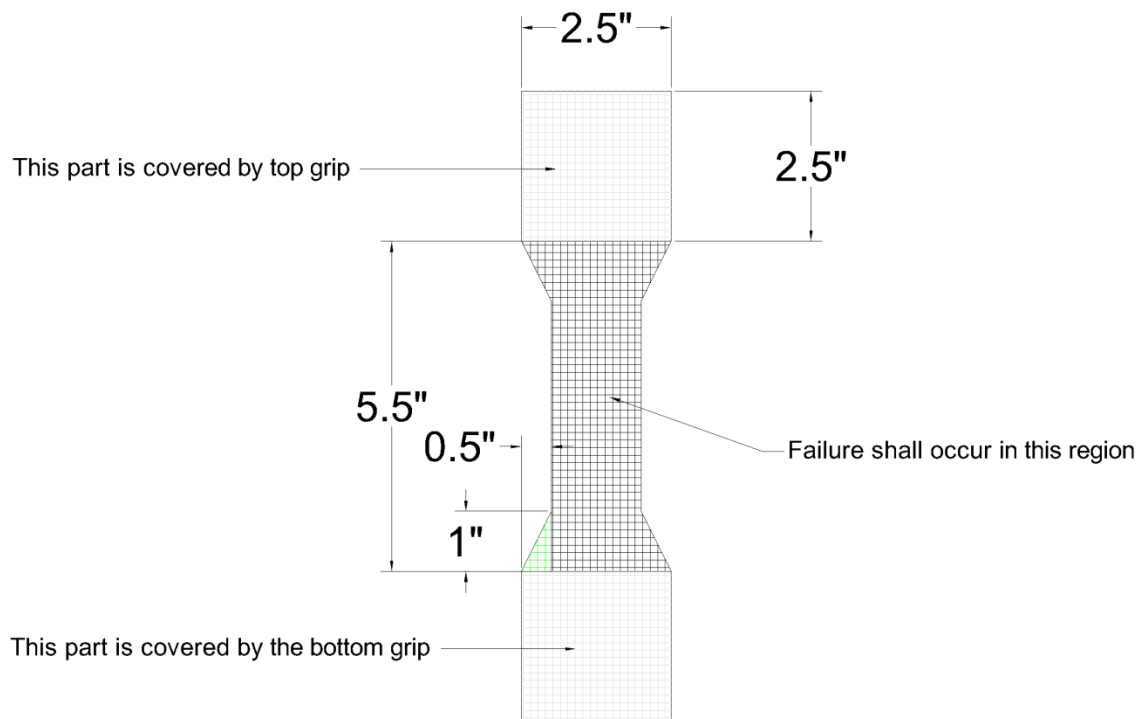
### **2.2.3 Tension Test on the Carpet**

#### **2.2.3.1 General information and configuration**

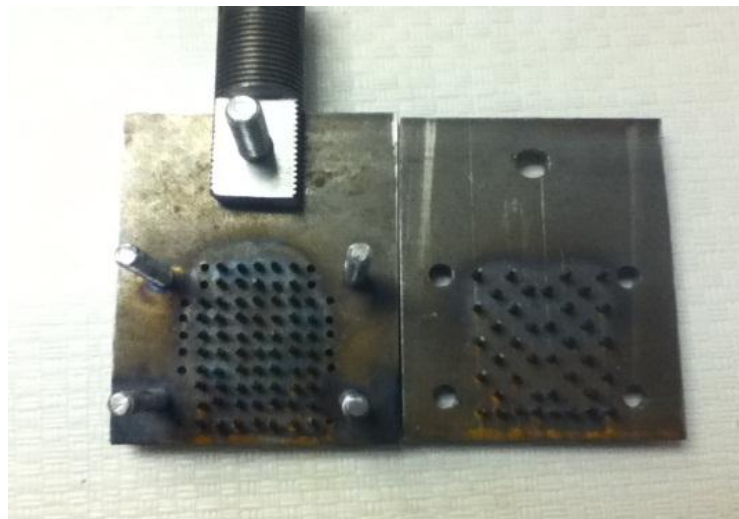
Because there is no standard test to assess the tensile properties of carpets, we have developed a test. Dog-bone shape samples were chosen so that they force the failure to occur at the middle of the carpet and not at the grips. The total length of the samples is 10.5" where the middle is 1.5" wide as it matches the width of the composite specimens. And finally the top and bottom part of the dog-bone was designed to be 1" wider than the middle part. Fig. 2-8 shows the general configuration of the carpet specimen used for the tension test.

#### **2.2.3.2 Heads (Grips)**

As shown on fig. 2-9 the grips consist of two metal plates with numerous pins being welded to them to grasp the carpet ends. Aligning the sample and the grips should be done so that the grips will not exert any excessive stress due to eccentric loading.



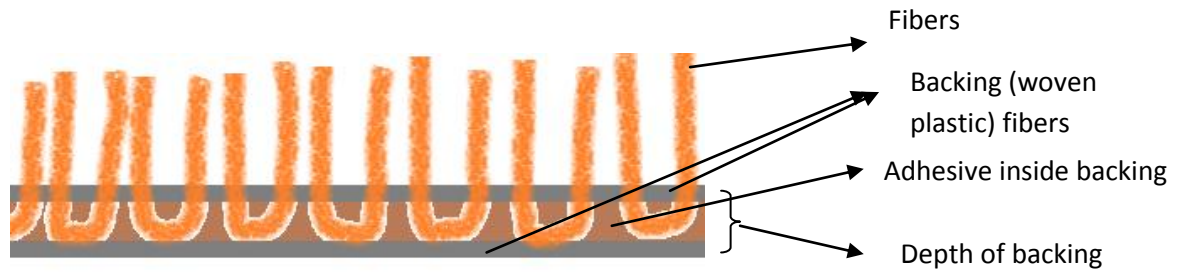
**Figure 2-8: General layout of carpet specimens for tension test**



**Figure 2-9: The grips used for carpet tension test**

### 2.2.3.3 Test speed and test setup

Constant head speed with relative grips displacement at 0.3 in/min was used for this test. Since measuring the exact effective area of the carpet backing is very hard, providing the stress-strain diagram for the carpet may yield unrealistic values. Therefore, for analysis purpose load versus displacement data is directly used in the section analysis of the composite material. More information about implementing the data from carpet test in to section analysis is provided in the discussion section. Fig. 2-10 shows a section from the carpet used in the tests.



**Figure 2-10: carpet section view**

The failure is considered when the adhesive material inside the carpet backing fractures. This point coincides with the peak point in the load displacement diagram for the carpet in tension. However, at this point the carpet is not yet split into two pieces. Fig. 2-11 demonstrates the carpet specimen in the test setup at failure.

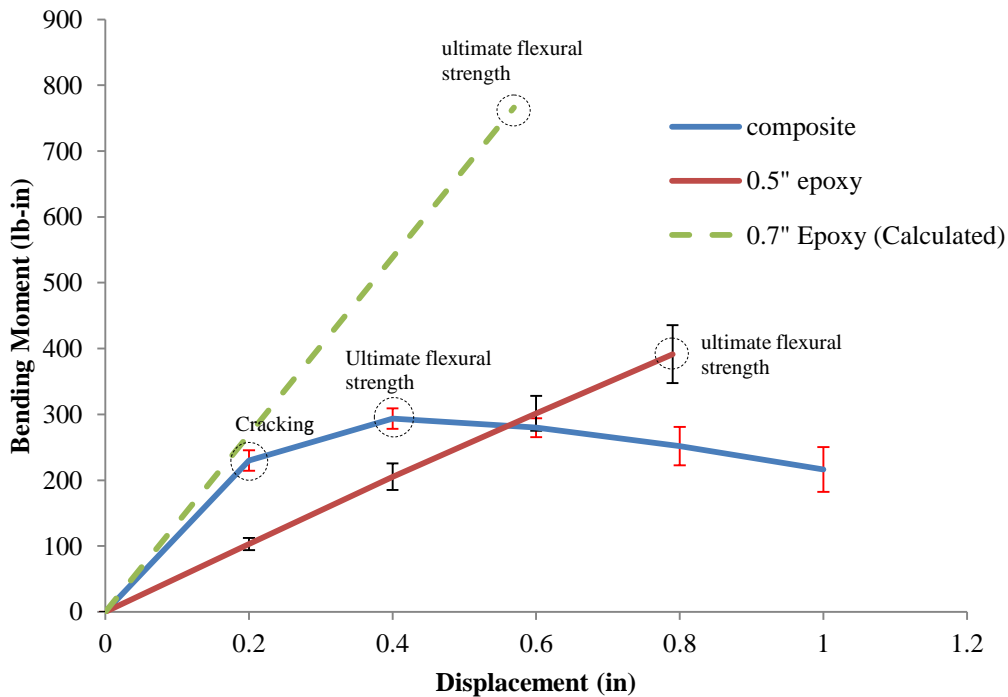


**Figure 2-11: carpet sample in tension test**

## 2.3 Results

### 2.3.1 Epoxy and composite samples in flexure

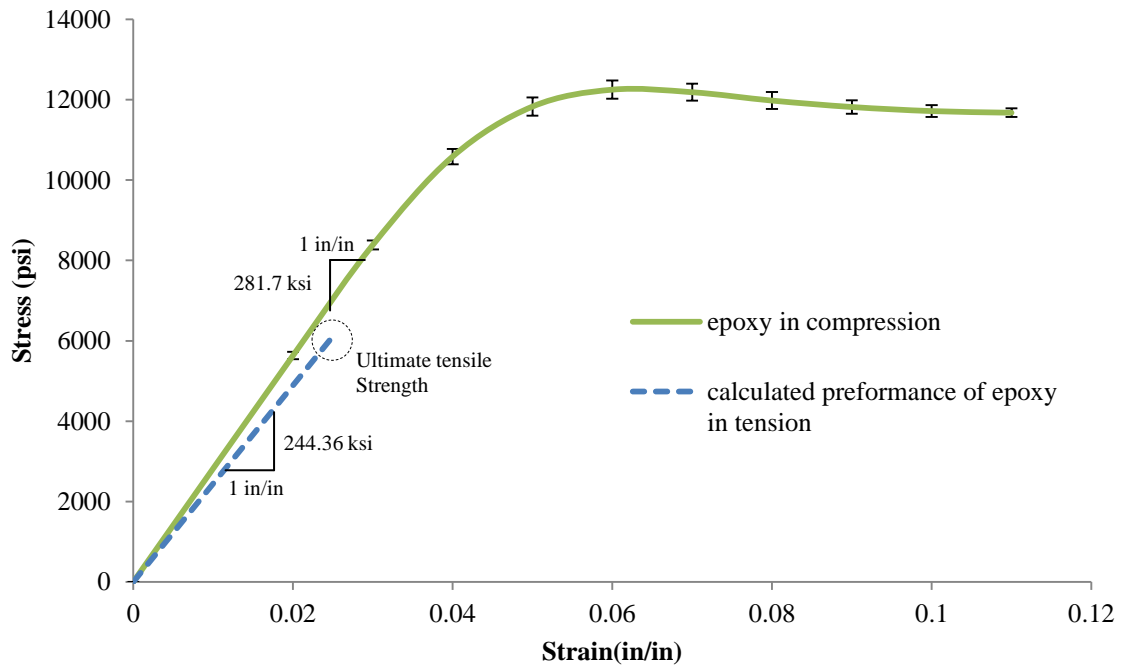
As discussed in section 2.2.2 the tests were performed on epoxy samples of 0.5" deep while the composite samples in the tests were 0.7" deep. To make closer comparison between the epoxy performance versus composite performance the moment-deflection diagram was estimated for an epoxy sample of 0.7" deep which matches the composite sample depth and shown in the diagram in dashed line. The estimated diagram for 0.7" epoxy samples is determined based on the calculated properties of the epoxy portrayed in section 2.4.1. Fig. 2-12 shows the bending moment vs. deflection at midspan for the composite and the epoxy samples in flexure.



**Figure 2-12: Moment vs. Deflection diagram of the epoxy and the composite in flexure**

### 2.3.2 Epoxy in Compression

Fig. 2-13 shows the Stress-Strain diagram for the epoxy cylinders tested in compression. Since testing the epoxy in tension was not possible in this work, tensile behavior of the epoxy in tension was determined based on compressive and flexural behavior of the epoxy explained in 2.4.1. The expected Stress-Strain diagram for the epoxy in tension is shown in dashed line.

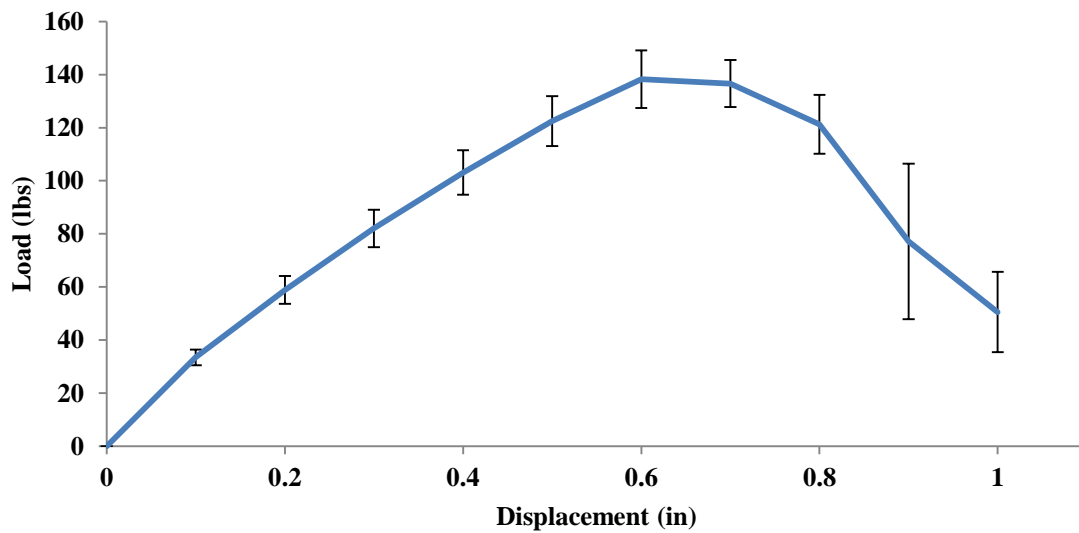


**Figure 2-13: stress-strain plateau of epoxy under axial load**

As shown on fig. 2-13 the stiffness of the epoxy in tension and compression are very similar. However, the ultimate strength of the epoxy is approximately 100% more in compression compared to tension. Also it can be seen from the diagram that the failure of the epoxy in tension is brittle while the epoxy in compression has a large nonlinear portion where the material strains with no large loss in strength.

### 2.3.3 Carpet in tension

As mentioned before because there is not a practical way to measure the net area of the carpet, it was decided that the carpet would not be evaluated based on the stress and strain. Since the width of the carpet tested in tension matches the width of the composite samples, the tensile load resisted by the carpet is used directly for section analysis of the composite sample. Fig. 2-14 shows the load-displacement plot for the carpet in tension.



**Figure 2-14: Load-Displacement diagram for carpet sample in tension**

## **2.4 Discussion**

### **2.4.1 Epoxy in flexure**

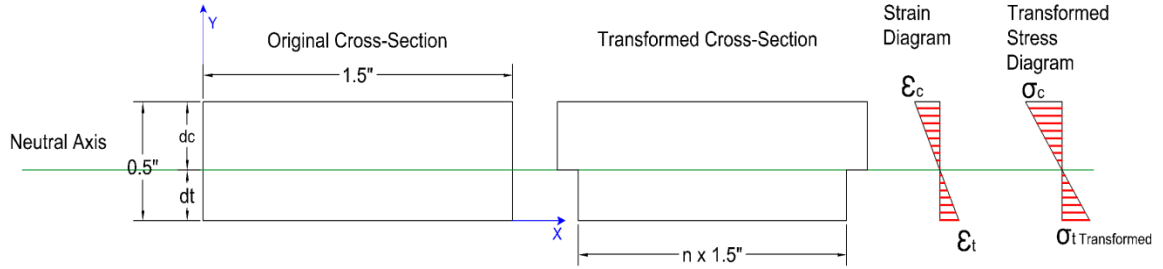
As mentioned before epoxy was not directly tested in tension. However, tensile properties of epoxy have significant importance in providing a section analysis for the carpet composite material. Therefore, a theoretical approach was used to determine the properties of epoxy in tension. In this section, the results from flexural test on epoxy beam and compression test on epoxy cylinders are used to better understand the behavior of epoxy in flexure and ultimately determine the properties of the epoxy in tension that will be used in composite section analysis.

Looking at fig. 2-12 we can see that the moment-deflection diagram for the epoxy in flexure is linear. This means that the material does not yield before failure. It also means that the stress over the depth of the cross section remains linear through loading and until failure. However, from fig. 2-13 it can be seen that the epoxy in compression does yield and the stress-strain diagram has a nonlinear portion. This indicates that the epoxy in tension is weaker and it fractures before the epoxy in compression yields or enters the nonlinear portion of the stress-strain diagram. Therefore, it can be assumed that epoxy both in tension and in compression stress linearly until the material fails. In this case classic Euler-Bernoulli beam theories can be applied in analysis of the epoxy sample.

As seen in other materials the strength and the modulus of elasticity of the epoxy in tension and compression may not be the same. That is why the epoxy itself acts as a composite material with two components with different properties. One component is the compressive epoxy and the other is tensile epoxy. Nevertheless, the line between the two components is drawn where the neutral axis lies. Above the neutral axis we have the epoxy with compressive properties and below that we have the epoxy with tensile properties. In order to be able to use classic beam equations, the section needs to be transformed to a uniform material. Since the epoxy was tested



in compression, and the compressive properties of the epoxy is known based on the test results, the epoxy below neutral axis or epoxy in tension has been transformed with the modular ratio to compressive epoxy for the flexural analysis. The transformed cross section of the composite sample is shown on fig. 2-15.



**Figure 2-15: transformed cross section of the epoxy in flexure**

It is very important to mention that all the derivations in this section are based on the transformed epoxy section. From fig. 2-15 eqn. 2-2 could be written where “ $\sigma_{t \text{ Trans}}$ ” is the equivalent tension stress for the transformed cross-section at the bottom extreme fiber.

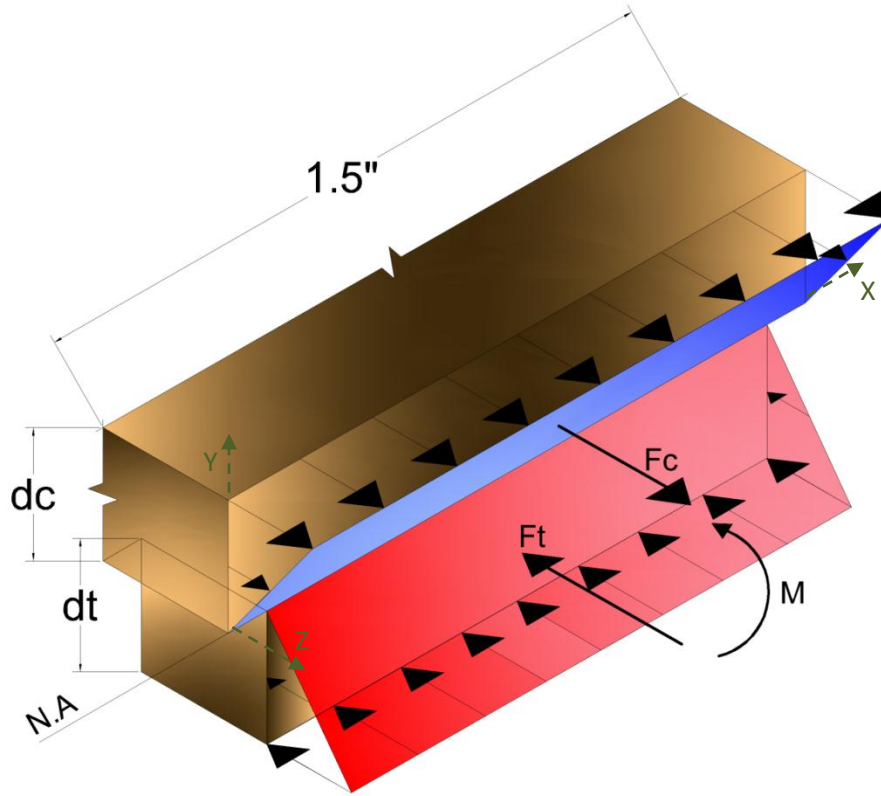
$$\frac{\sigma_c}{\sigma_{t \text{ Trans}}} = \frac{\varepsilon_c}{\varepsilon_t} = \frac{d_c}{d_t} \rightarrow \sigma_{t \text{ Trans}} = \sigma_c * \frac{d_t}{d_c} \quad (2-2)$$

Fig. 2-16 shows the external forces and the stress diagram over the transformed cross section of the epoxy at the mid span. Since no axial load acts on the epoxy beam, the equilibrium of forces in the longitudinal direction of the beam should be satisfied so the resultant forces in compression and tension over the section will be equal and in opposite direction.

$$\Sigma F_z = 0$$

$$\left(\frac{1}{2} * \sigma_c\right) * d_c * 1.5 - \left(\frac{1}{2} * \sigma_{t \text{ Trans}}\right) * d_t * n * 1.5 = 0$$

$$\left(\frac{1}{2} * \sigma_c\right) * d_c * 1.5 = \left(\frac{1}{2} * \sigma_{t \text{ Trans}}\right) * d_t * n * 1.5 \quad (2-3)$$



**Figure 2-16: stress diagram over the transformed epoxy cross-section**

“n” in eqn. 2-3 is the modular ratio that is the ratio of modulus of elasticity of the epoxy in tension to the modulus of elasticity of the epoxy in compression. Simplifying eqn. 2-3 the modular ratio can be calculated as:

$$n = \frac{\sigma_c}{\sigma_{t \text{ Trans}}} * \frac{d_c}{d_t} \quad (2-4)$$

Substituting “ $\sigma_{t \text{ Trans}}$ ” from eqn. 2-2 to eqn. 2-4, modular ratio can be solved in terms of “ $d_c$ ” and “ $d_t$ ”.

$$n = \frac{d_c^2}{d_t^2} \quad (2-5)$$

Transformed moment of inertia is now calculated in terms of “ $d_c$ ”, “ $d_t$ ” and “ $n$ ”. This will be used to reduce our unknowns.

$$I_{Trans} = \frac{1}{3} * 1.5 * d_c^3 + \frac{1}{3} * n * 1.5 * d_t^3 \quad (2-6)$$

Substituting “ $n$ ” from eqn. 2-5 in to eqn. 2-6 it yields:

$$I_{Trans} = \frac{1}{2} * d_c^3 + \frac{1}{2} * \frac{d_c^2}{d_t^2} * d_t^3$$

$$I_{Trans} = \frac{1}{2} * d_c^2 * (d_c + d_t)$$

$$I_{Trans} = \frac{1}{4} * d_c^2 \quad (2-7)$$

Since “ $d_c+d_t$ ” is the depth of the epoxy section which is 0.5” the transformed moment of inertia can be determined only in terms of “ $d_c$ ”. On the other hand the transformed moment of inertia can be determined with a different approach based on beam mechanics. The boundary condition for epoxy beam as shown in fig. 2-7 can be considered as simply supported. For a simply supported beam with point load applied at the center we have:

$$\delta = \frac{P * L^3}{48 * E_c * I_{Trans}} \quad (2-8)$$

Where “ $\delta$ ” is the deflection of the epoxy beam at the center of the span, “ $P$ ” is the point load at midspan and “ $L$ ” is the span length for the epoxy sample. Here, this equation is used for the transformed section where the modulus of elasticity of epoxy in compression and the transformed moment of inertia are to be used in denominator. In eqn. 2-8 all the parameters except transformed moment of inertia are known based on the test results. Looking back at fig. 2-12 the maximum bending moment for the epoxy beam is shown on the diagram. From beam mechanics for a simply supported beam with a point load on midspan, the maximum bending moment at the center of the beam can be determined from “ $M=P*L/4$ ”. Having the maximum bending moment and the span length the maximum point load is calculated as 0.156 kip. Also at the corresponding

point the deflection of the midspan can be determined from the horizontal axis of fig. 2-12. In Fig. 2-7 the span length of the epoxy beam is shown as 10". And finally, modulus of elasticity of the epoxy in compression can be determined from the slope of the linear portion of the stress-strain diagram (Fig. 2-13) that is 281.7 ksi. Inserting all the mentioned parameters in eqn. 2-8 we can solve for " $I_{Trans}$ ":

$$I_{Trans} = \frac{0.156 \text{ kip} * 10^3 \text{ in}^3}{48 * 281.7 \text{ ksi} * 0.79 \text{ in}} = 0.0146 \text{ in}^4$$

Now that the transformed moment of inertia is quantified, using eqn. 2-7 the distance between the extreme fibers in compression to the neutral axis can be determined:

$$0.0146 = \frac{1}{4} * d_c^2 \rightarrow d_c = 0.241 \text{ in}$$

" $d_t$ " can be found by deducting " $d_c$ " from the depth of the epoxy sample which yields 0.259".

Now using eqn. 2-5 modular ratio is found to be 0.866. This means that the epoxy is stronger in compression than in tension and consequently an equivalent area of the tensile epoxy is smaller when transformed to compressive epoxy. This is demonstrated in fig. 2-15 and fig. 2-16. At this point the stress of the epoxy in compression and tension needs to be determined. Looking at fig. 2-16 from the equilibrium of bending moments on the cross-section we can write eqn. 2-9 where  $M$  is the external bending moment at midspan.

$$M - \left(\frac{1}{2} * \sigma_c\right) * d_c * 1.5 * \frac{2}{3} * d_c + \left(\frac{l}{2} * \sigma_{tTrans}\right) * d_t * n * 1.5 * \frac{2}{3} * d_t = 0 \quad (2-9)$$

Substituting eqn. 2-2 into eqn. 2-9 and replacing " $M$ " with maximum bending moment at midspan at failure of the epoxy beam (fig. 2-12) we have:

$$0.391 \text{ kip.in} = \left(\frac{1}{2} * \sigma_c\right) * 0.241 * 1.5 * \frac{2}{3} * 0.241 + \left(\frac{1}{2} * \sigma_c * \frac{0.259}{0.241}\right) * 0.259 * 0.866 \\ * 1.5 * \frac{2}{3} * 0.259$$

$$\sigma_c = 6.489 \text{ ksi}$$

This means that at the point that the epoxy beam fractures the stress at top compression chord is 6.489 ksi. As seen on fig. 2-12 the epoxy in compression does not yield until after it is stressed to 8.0 ksi. This confirms the original assumption of the epoxy not going within the nonlinear portion of the stress-strain diagram in compression before failure. It also confirms that it is legitimate to use the compressive modulus of elasticity of the epoxy that corresponds to the linear portion in the past derivations.

From eqn. 2-2 the equivalent maximum tension stress for the transformed epoxy section “ $\sigma_{\text{IT}}$ ” can be determined as 6.974 ksi. This is not the actual tension stress in the epoxy. In fact the equivalent tension stress needs to be multiplied by the modular ratio to calculate the actual tension stress in the epoxy at failure. The actual maximum stress can be calculated as 6.04 ksi. Also the top chord strain of the epoxy can be computed by dividing the compression stress “ $\sigma_c$ ” by the modulus of elasticity of the epoxy used earlier in the equations. Using the strain compatibility the ultimate strain of the epoxy in tension at failure can be calculated based on the strain of the epoxy in compression. And finally, the modulus of elasticity of the epoxy in tension can be found using the ultimate stress and strain of the epoxy at failure. Table 2-2 summarizes the properties of the epoxy calculated in this section.

**Table 2-2: epoxy properties based on three points flexural test**

Measured properties of epoxy	
dimensions of the epoxy samples	1.5"x0.5"x12"
span length	10 in
compressive modulus of elasticity ( $E_c$ )	281.7 ksi
ultimate resisting bending moment (M)	0.391kip-in
transformed moment of inertia ( $I_T$ )	0.0146 in <sup>2</sup>
Calculated properties of epoxy	
tensile modulus of elasticity ( $E_t$ )	244.36 ksi
ultimate strength of epoxy in tension ( $\sigma_t$ )	6.04 ksi
compressive stress in epoxy at failure ( $\sigma_c$ )	6.49 ksi
maximum tensile strain ( $\epsilon_t$ )	0.0247 in/in
maximum compressive strain at failure ( $\epsilon_c$ )	0.023in/in
depth of neutral axis from bottom	0.259 in

The data shown on table 2-2 indicates that when the epoxy beam fails in flexure, the epoxy in compression is stressed only about half of the compressive ultimate strength. This confirms that the epoxy in tension is the weaker link. In other words, the epoxy in tension fails before the epoxy in compression reaches the ultimate strength. It can be concluded that for any epoxy section subjected to flexure, the failure occurs when the extreme fiber in tension reaches the ultimate strength that is 6.04 ksi or approximately 6.0 ksi. Moreover, the epoxy both in tension and in compression stresses and strains linearly through flexural loading and until failure. Thus, the stress distribution will remain compatible for any given rectangular cross-section with given dimension. Therefore, it can be concluded that for any rectangular epoxy sections the location of the neutral axis should be proportional of what calculated in this section. For instance, the distance of the neutral axis was calculated to be 0.241" from the top of the section for the 0.5" deep epoxy section. For any rectangular section of depth "d" the distance of the neutral axis to the top of the the section will be 0.481 times "d".

According to the previous paragraph, for an epoxy sample of 0.7" deep by any given width, the location of the neutral axis can be found based the location of the neutral axis

determined for 0.5” deep sample tested in this work. By compatibility the distance of the neutral axis to the top chord for a 0.7” deep sample can be calculated as “ $0.7 \times 0.481$ ” that is 0.337”. Now, the tensile stress at very bottom fiber should be set to 6.04 ksi and the compressive stress can be found by strain compatibility over the section. Finally, the bending resistance of the section is determined by finding the resultant tension and compression forces over the cross section and multiplying by their moment arms. This is the approach used to estimate the bending moment vs. deflection plateau for a 0.7” by 1.5” epoxy sample shown as dashed line on fig. 2-12. More detailed calculation for this part is provided in Appendix A.

For nonrectangular cross-sections, the location of the neutral axis is not proportional to the tested sample any more. To find the neutral axis for nonrectangular cross section, again the stress at the extreme tension fiber is to be set to 6.04 ksi. Through trial and error the location of the neutral axis and so the stress at extreme compressive fiber needs to be found so that the resultant forces on the section, above and below the neutral axis satisfy the equilibrium of the section. This concept is used in section analysis for the composite material. More detail about this approach is provided in 2.4.5.

#### **2.4.2 The carpet composite in flexure**

The purpose of this section is to provide an analysis to describe the carpet composite sample performance in flexure. As seen on fig. 2-12 the overall flexural behavior of the carpet composite could be simplified as a bilinear behavior. First, the composite follows a linear stress-strain behavior until the cracks form on the tension face. After losing some stiffness the sample continues to resist more bending moment until the ultimate strength is reached.

### 2.4.3 Contribution of the carpet in flexural behavior of the composite material

In this section the effect of carpet in the tensile face of the composite material is discussed. Finding the exact cross sectional area for the carpet is not possible since the carpet consist of numerous fibers and some adhesive. Therefore, as shown on fig. 2-14, the carpet behavior in tension is shown based on the load-displacement diagram instead of Stress-Strain curve. However, the value of strain for the carpet is computable and could be used in section analysis. As calculated in 2.4.1 and shown on table 2-2 maximum tension stress in the epoxy at failure is 6.04 ksi and strain is 0.0247 in/in. At the same strain value, the elongation of the carpet is 0.136". At the point of failure the carpet is strain only to 28% of the ultimate tensile capacity that is approximately 41 lbs. This number is very small compared to the tensile strength provided by the epoxy. The tensile block of epoxy sample just before failure resists a total force of 1,173 lbs which is more than 28 times the tensile resistance the carpet can provide at failure. Although these values may be reduced in composite sample because the epoxy content is less due to air voids and carpet fibers, still the contribution of the carpet in tension remains small compared to epoxy. The carpet also cannot considerably assist the composite after the cracks form on the bottom of the sample. *Thus, it can be concluded that the carpet strength does not attribute to the bilinear flexural behavior or the extra bending resistance of the composite after cracking. For this reason, the tensile strength of the carpet is ignored in the analysis of the composite section.*

### 2.4.4 Bilinear behavior of the composite in flexure

As explained in the previous section due to insufficient tension capacity of the carpet, the bilinear behavior of the carpet composite samples cannot be caused by the tensile strength of the carpet. The key to describe the bilinear behavior of the composite material is the difference between the air content in the bottom layer of the composite compared to the middle area. The



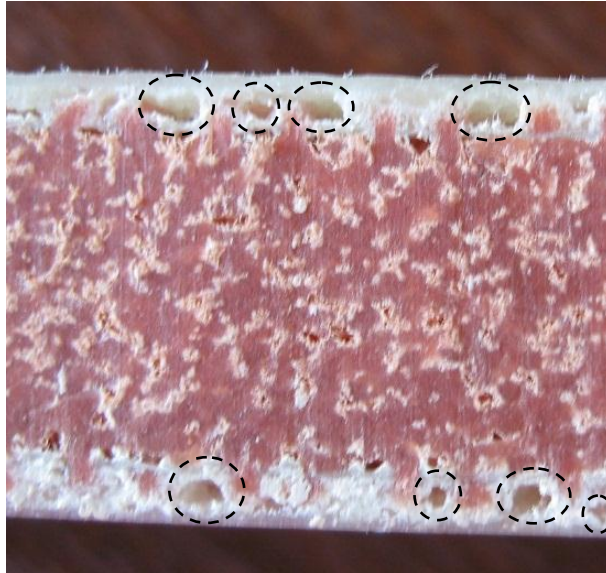
carpet backing at the top and bottom of the composite sample resist the absorption of epoxy in these areas during fabrication process. This reduces the epoxy content in these areas in the composite sample. When the extreme fiber of the composite in tension is at ultimate stress, epoxy right above the backing layer is not yet at its limit. Since the epoxy content right above the backing area is more than the epoxy content in the bottom layer, after the cracks form on the bottom layer, stress redistributes and the larger area of epoxy reaches to the ultimate stress which provides more bending resistance.

#### **2.4.5 Proposed model for carpet composite in flexure**

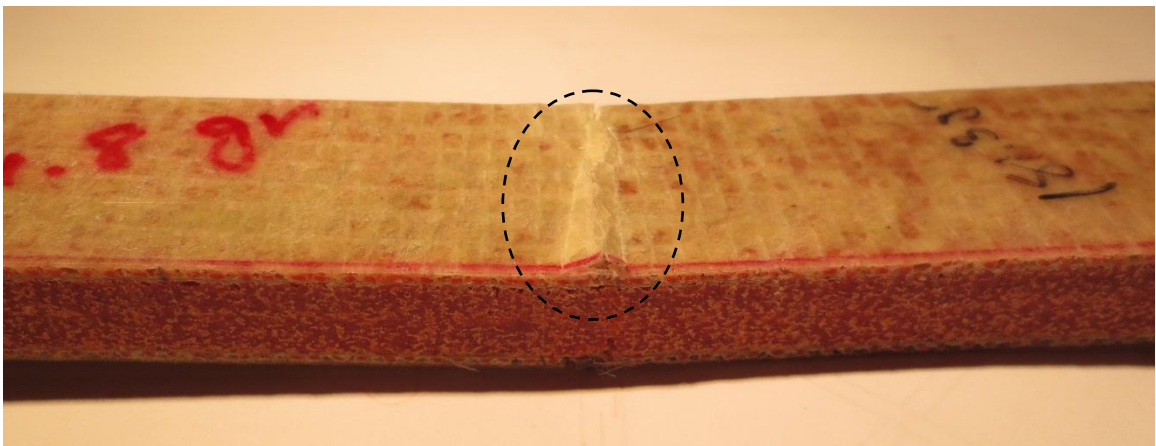
As just mentioned and can be seen on fig. 2-17 the carpet backings resist the penetration of epoxy into the top and bottom layers of the composite material where the carpet backings are located. Large air voids seen in this region confirms that the epoxy content in this area is less than the middle part of the sample. On the other hand the carpet in the top layer of the composite is not capable to resist any compressive load as they are often noticed to buckle early in the loading. Also for the very thin layer of the absorbed epoxy and backing near the surface of the composite, no measurable load path is provided with the core epoxy of the composite. Therefore, due to poor load transfer the very thin layer of epoxy on the compression face buckles at early stage of loading and will not be able to resist any load thereafter (fig. 2-18). For this reasons it is assumed that the top layer (0.1") of the composite material can be ignored in flexural analysis.

The middle part of the composite profile consists of epoxy, air voids and carpet fibers. Looking back at fig. 2-9, the extended fibers from the carpet backing are theoretically laid out perpendicular to the direction of applied flexural loading. They may change orientation after being compacted through VARTM fabrication process, yet they cannot provide any resistance as they are poorly attached to the carpet backing. In fact, these fibers are very loosely attached to the

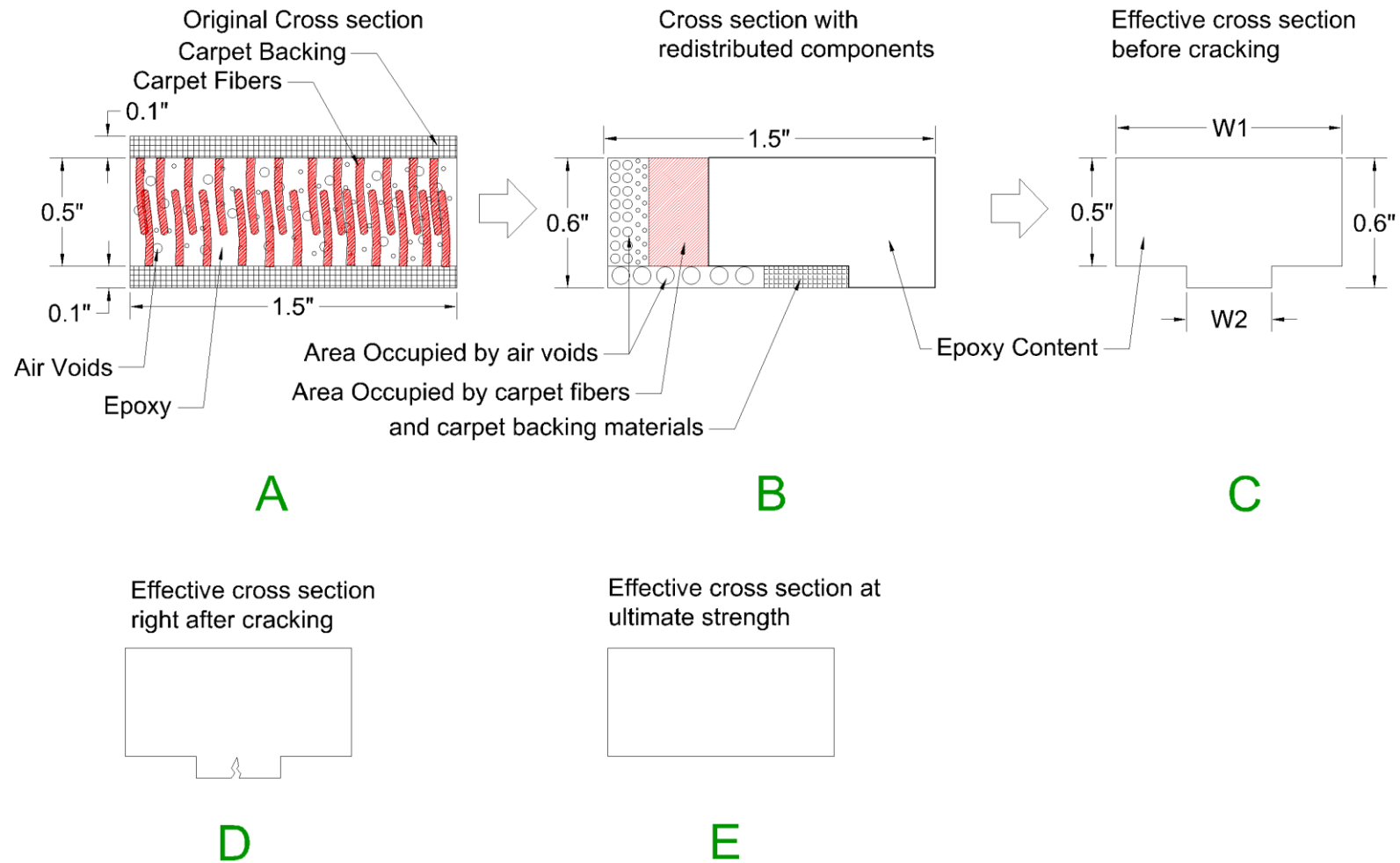
backing that could easily be removed from the carpet backing with moderate force. Fig. 2-19 “A” illustrates a schematic of the composite section.



**Figure 2-17: large air voids in the carpet backing areas**



**Figure 2-18: buckling of the top layer (epoxy and carpet backing mix) in a failed sample**



**Figure 2-19: Effective cross section of the composite at cracking and ultimate flexural strength**

The bottom layer of the composite consists of mostly carpet backing materials, large air voids and some epoxy. This layer could be accounted for resisting some tensile load. However, as soon as the sample cracks this layer cannot resist any more loads. This means that the effective resisting cross section after cracking and at ultimate strength of the composite is only the middle part of the composite (Fig. 2-19 C to E)

The middle part of the composite profile could be considered as diluted epoxy where epoxy is the only material resisting the flexural load. The fibers in this region are assumed not to contribute to the flexural strength of the composite. Now since the strength and behavior of the epoxy in both compression and tension is modeled, finding the percentage of epoxy in the middle region will lead to accurate estimation of ultimate strength of a composite sample in flexure.

Looking back at fig. 2-17 it can be seen that other than carpet backing region the distribution of air voids throughout the middle part of the cross-section is fairly uniform. Therefore, it is assumed that the air voids are distributed uniformly along the width and depth of the profile in the middle region. Fig. 2-19 shows the equivalent effective cross-section of the composite sample in flexure at cracking and ultimate strength.

Looking at Fig. 2-19, it can be seen that the effective cross section at ultimate failure is an epoxy with a given width. The depth of the epoxy is the depth of the original composite cross section minus the 0.1" layer on top and bottom. As stated before the top 0.1" of the composite consists of carpet backing which buckles in early stage of loading and the bottom 0.1" consists of carpet backing and epoxy which cracks before ultimate failure is reached. Therefore, it is assumed that these two layers are not effective at ultimate failure. To find the epoxy content we can compute the bending moment that can be resisted by an epoxy sample that is 1.5" wide and 0.5" deep (original composite dimensions minus top and bottom backing layers) and compare that to the actual ultimate bending moment the composite sample provides.

Locating the position of the neutral axis using the same approach outlined in 2.4.1, the bending resistance for the epoxy sample of 1.5” wide and 0.5” deep yields a moment of 0.391 (kip-in) which is the same as test results as the dimensions of the epoxy samples match these dimensions. The ultimate bending moment provided by the carpet composite sample in the laboratory test is 0.290 kip-in, which is approximately 74% of the bending capacity provided by the epoxy sample. This means that approximately 26% of the middle section – excluding the top and bottom layer of carpet backing – of the composite consists of air voids and carpet fibers and 74% epoxy.

This analysis suggests that for a given carpet composite sample made with the same procedure that was used for the samples in this work, the ultimate bending capacity of the cross section can be computed by calculating the bending capacity of an epoxy sample of the middle depth of the composite and 0.74 times the width of the composite sample.

For simplification of analysis it is easier to analyze the section at ultimate strength first. This way the epoxy content in the middle part of the composite will be determined. Finding the epoxy content in the middle part of the composite, to find the cracking moment, the epoxy content in the bottom layer of the composite is to be found. For different epoxy contents in the backing region, the location of the neutral axis and the bending moment in which the extreme fiber in tension cracks should be computed. The epoxy content in the backing area could be back calculated so that uncracked cross section provides the bending resistance that matches the bending moment of the composite at cracking from laboratory results. Through iteration, epoxy content of 8% at the backing layer provides 0.229 (kip.in) of bending resistance right when the extreme fiber in tension is at cracking stress. More details about estimating the flexural capacity of nonrectangular sections is provided in appendix A.

The carpet composite material as mentioned before is an untraditional composite. The epoxy used to encapsulate the carpet and backing material is stronger than the carpet and backing. This means that the carpet could not be expected to reinforce the epoxy. From the previous discussion it can be concluded that by adding the carpet to the composite material, the epoxy is diluted with air and the weaker carpet. The model however is developed based on the properties of epoxy only and determining the effective cross section of the epoxy in each stage. It is realized that the model provided does not represent the composite material as a new continuum with new properties and the original dimensions; instead the model is a simplified representation of the composite that describes the behavior and provides a close estimate of the composite strength.

#### **2.4.6 Summary of the method**

To analyze the composite cross section with arbitrary dimensions the effective epoxy cross section is to be determined at cracking and ultimate failure. To determine the effective cross section at cracking first the top layer of carpet backing which is 0.1" deep in average should be assumed ineffective. Then width of the middle section should be multiplied by 0.74 to find the effective width while the depth remains the same. And finally the width of the bottom layer with carpet backing should be reduced by 8%. The remaining section as seen on fig. 2-18 is considered as just epoxy. To find the strength of the effective cross section at cracking neutral axis is to be determined based on the cross section equilibrium and the ultimate tensile strength at cracking that is 6.04 KSI. Due to brittle nature of the epoxy in tension the failure always start on the tensile face of the sample. The resisting bending moment could be found based on the provided stress-strain plot of the epoxy in tension and compression.

Similarly to find the ultimate failure strength of the composite section the effective epoxy section needs to be determined. In order to find the effective cross section at ultimate strength the bottom layer of 0.1" deep epoxy should be ignored. Again the neutral axis is to be determined

based on the equilibrium on the cross section and stress-strain plateau of the epoxy in tension and compression.

#### **2.4.7 Conclusion**

In this work, tests were performed to evaluate the strength and other properties of individual components of the carpet composite material. The carpet used in the composite material was tested in tension and the epoxy was tested in both compression and flexure. Testing epoxy in tension was not possible in this work. Therefore, a theoretical approach was used to determine the behavior of the epoxy in tension using the data from flexural and compression test. It was determined that the epoxy is weaker and has a reduced modulus in tension compared to compression. Moreover, the epoxy in tension has a brittle failure and does not yield before it fails while the epoxy in compression yields excessively after it reaches the maximum resisting strength. In the same regard, the epoxy section in flexure was analyzed and the flexural behavior of the epoxy was disclosed.

Comparing the strength of epoxy in tension with the tensile strength of the carpet, it was concluded that the carpet does not contribute to the flexural strength of the composite material. Furthermore, the carpet and the backing on the top of the composite samples may not resist much compressive load as they often have been observed to buckle in early stage of loading. Consequently, it was concluded that the epoxy is the only material that defines the strength of the composite. To estimate the flexural capacity of the carpet composite material, effective epoxy cross-section was determined.

The carpet composite material investigated follows a bilinear behavior in flexure. The behavior is linear up to the point where cracks form in the epoxy layer inside the carpet backing region. Then, the composite loses stiffness but continues to resist more bending moment until the maximum capacity is reached. Finally, the flexural capacity of the composite reduces gradually.

The bilinear behavior of the composite material is resulted due to difference in the epoxy content in the middle layer and the bottom layer of the composite. Since the carpet backing resists the penetration of the epoxy in the bottom layer, the epoxy content is less in the carpet layer when compared to epoxy core of the composite section. The difference between the epoxy content in the extreme layer and the core of the composite causes the bilinear behavior.

As the sample is loaded, the bottom fiber in tension of the epoxy in the composite reaches the ultimate stress and cracks form in the bottom layer of the composite. At this point the composite material loses stiffness but stress redistribution occurs over the epoxy content of the composite section. Gradually, stress increases on the layer immediately above the carpet backing layer. The epoxy content in the layer above the carpet backing is higher and so there is more material to reach higher stress. This provides higher flexural resistance. Finally, when the tensile stress reaches the ultimate capacity of the epoxy cracks start to form in the layer above the carpet backing and the composite starts to loose strength.

Overall, using the carpet as reinforcing material in the epoxy as the medium, does not improve the strength of the new composite. As seen on fig. 2-12 the ultimate flexural strength of the composite used in this work is only 38% of an epoxy section of same dimensions with no carpet reinforcing. While this shows considerable reduction in flexural strength the use of carpet in the epoxy does improve the ductile performance of the carpet composite material. Although, the epoxy has shown brittle failure in flexure, the composite material shows a significant ductility after the ultimate strength is reached. Ductility is of fundamental importance for structural members. For the proposed application of the composite material which is the sound walls that are to be installed near highways, brittle failure can be catastrophic.



## **CHAPTER III**

### **FUTURE WORKS AND RECOMMENDATIONS**

#### **3.1 Overview**

As seen in chapter 1 and 2 an overview of the composite material was presented based on the composing elements. Later, the composite material was tested in laboratory as well as individual composing materials. A model was presented to estimate the flexural resistance of the composite and also to describe the simplified behavior of the composite based on determining the effective epoxy area. In this section restrictions on the application of this study are explained as well as the challenges that were encountered in working with this novel composite material. Finally recommendations for future works are offered.

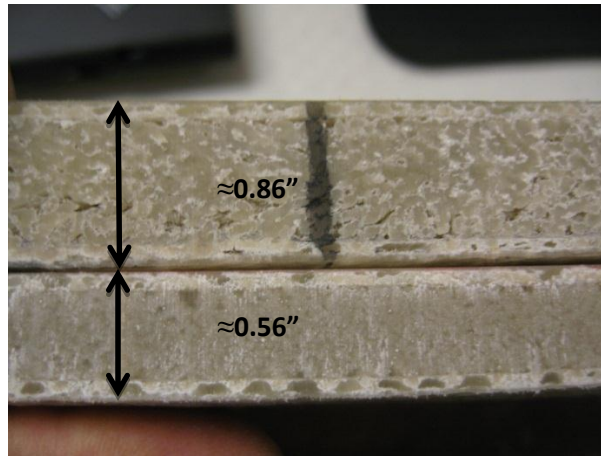
#### **3.2 Restrictions on application of the results of this study**

As mentioned before this study was performed while the manufacturing process of this novel material was being evolved. This affected the progress of this work as number of tests needed to be repeated and a lot left unused. The major issue with the data derived from the tests was the inconsistency and non-repeatability for different set of samples. As the samples were examined more thoroughly it was realized that some differences in samples are significant. Although it is totally understandable that the samples are handmade and each one may be to some extend different than the other based on different skill levels of the fabricator, there were some typical differences in the samples which should be avoided. These typical issues would fall in to

two general categories, non-uniform densities and using different carpets which will be explained respectively.

### 3.2.1 Non-Uniform Density

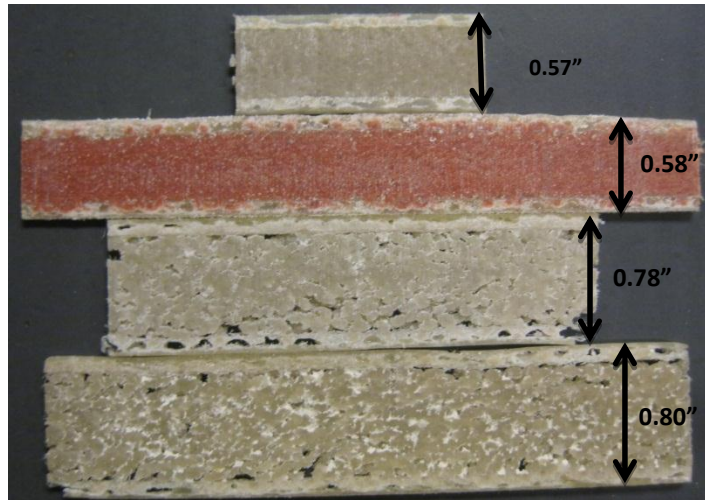
As can be seen in Fig. 3-1 samples did not have uniform thickness. Also looking closer one could see the air content or porosity is visibly different in two samples shown in the figure. This in turn causes difference in density of the samples which means the epoxy absorbed during vacuuming and the level to which vacuuming was performed on the samples could be different. When the densities of samples are not very close, it is difficult to normalize the results and to have comparable data. This directly affects the effective area of the cross section which the analysis is based on.



**Figure 3-1: section view of two samples from two different sheets**

The differences are more visible on fig. 3-2 where some slices of four random samples were cut and placed beside each other. It can clearly be seen that the depth and air content are different for all four samples. The difference in level of carpet saturation and level of compaction of the composite sample result in inconsistent density values for the samples. The density value for number of random samples is determined based on the average thickness of the sample and

tabulated in table 3-1. As can be seen the density of older samples are significantly off from new ones.



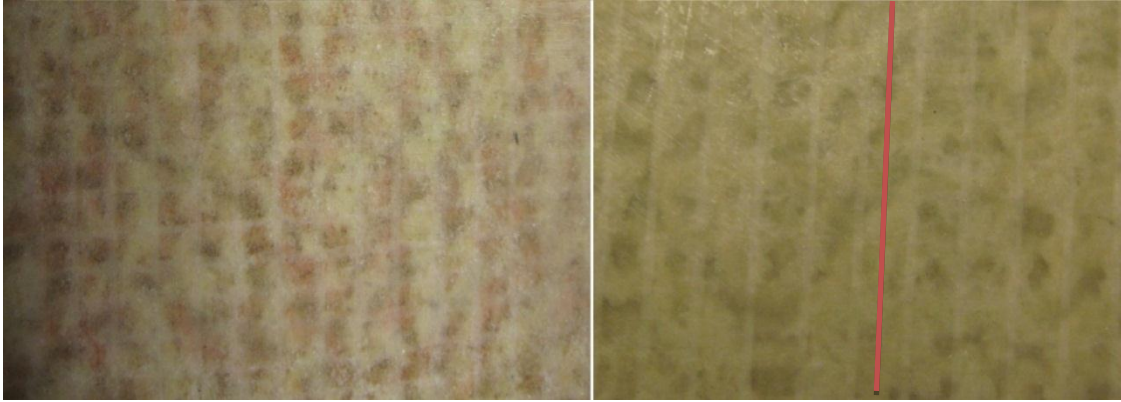
**Figure 3-2: cross section view of different samples**

**Table 3-1: density of different composite sample**

Sample	Density(lb/in <sup>3</sup> )
New I	0.035
New II	0.038
New III	0.04
New IV (with orange carpet)	0.041
Old I	0.0286
Old II	0.0299

### 3.2.2 Different Carpets:

Based on visual examinations, on the backing of the carpets used in older samples, the major fibers in one direction looked thicker whereas the ones perpendicular to them was thinner and less visible in the finished sample. Fig. 3-3 shows the newer samples on the left with fibers of same size in both orthogonal directions while the photo on the right shows a typical old sample with thicker fibers laid out vertically in the direction of the red indicator line and the horizontal are not well visible.



**Figure 3-3: top view of the new and old carpet backing inside the composite sample**

Since the older carpet was not available to be tested in tension a different carpet of same visual appearance was tested in tension in both directions of the thicker and thinner fibers and results suggested about 50% difference of tension resistance. Fortunately the carpet used in the newer samples did not show different resistance in tension when tested in different directions.

Sometimes imperfections were seen in some of the samples which resulted in premature failure. Most of them were seen in larger samples that were prepared for distributed load testing which is not presented in this paper.

Overall, although it is acknowledged that the manufacturing process was developing during this work, to provide a more general analytical approach that describes the behavior of composite material and provide a more accurate estimate of the flexural capacity, more tests needs to be performed on consistent samples. The consistency and repeatability of the tests is the key to better understand the behavior of this novel material in different loading conditions.

Based on the forgone discussion it was decided that for analysis purpose of the composite material in flexure and the results that are presented in this paper, only test data from the samples extracted from the latest sheet of composite material could be used. This means that the model provided in chapter 2 is only applicable for samples of the same level of compaction and so the

same air content with the same method of curing and the same carpet. In general the method presented in this paper is developed for a limited number of samples and differences may be found with change in epoxy viscosity, strength, carpet strength and air content produced by manufacturing process.

### **3.3 Future works and recommendations**

The composite material was originally proposed to be used as sound barrier on the highways. The flexural load is the major load that is subjected to these sound walls due to large surface area of sound barrier panels. However, there are other considerations that shall be taken into account to determine the suitability of this material for the proposed application. Connection between the composite panel and the posts and the required footing is of significant importance. To ensure sufficient load transfer between the composite panel and the posts more works needs to be done to determine the capability of the material in resisting shear loads.

When required consistency is achieved in fabricating the composite samples, some larger scale tests could be perform to confirm the results of this work. Also uniformly distributed load testing on this material is the best simulation of the actual loading condition which was started but not finished during this work. Beside the structural examinations, other studies on the integrity of the composite material against extreme weather conditions as well as fire exposure can provide a good insight to the future of this material. For instance, the level of toxic emission of the epoxy and the carpet in case of fire needs to be determined and the impact on environment and human health should be evaluated. Finally for this material to be substituted with any of current popular materials on the highways such as reinforced concrete more comparable data needs to be provided in terms of both structural performance and cost.

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## **STANDARDS**

ASTM D-883-11, “Standard Terminology Relating to Plastics”

ASTM D-695-10, “Standard Test Method for Compressive Properties of Rigid Plastics”

ASTM D6108-09, “Standard Test Method for Compressive Properties of Plastic Lumber and Shapes”

ASTM D-790-10, “Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials”

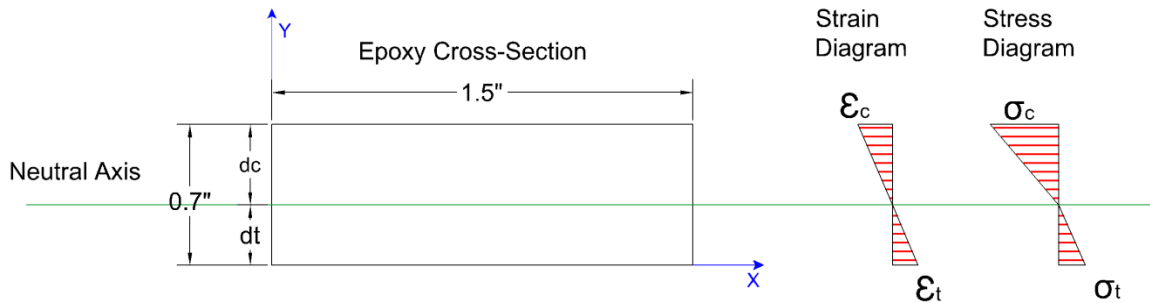
ASTM D3039/D3039M – 08, “Standard Test Method for Tensile Properties of Polymer Matrix Composite Material”

## APPENDECES

### APPENDIX A

#### A.1 Estimating flexural capacity for rectangular epoxy sections

As mentioned briefly in section 2.4.1 based on the findings of this work for the epoxy used in the composite sample, flexural strength can be determined for any rectangular and nonrectangular profiles. In this section, the approach already explained in this document is shown with more details and through numbers to estimate the flexural capacity of an epoxy section with different dimensions. Fig. A-1 shows the dimensions as well as the stress and strain diagram for an epoxy section.

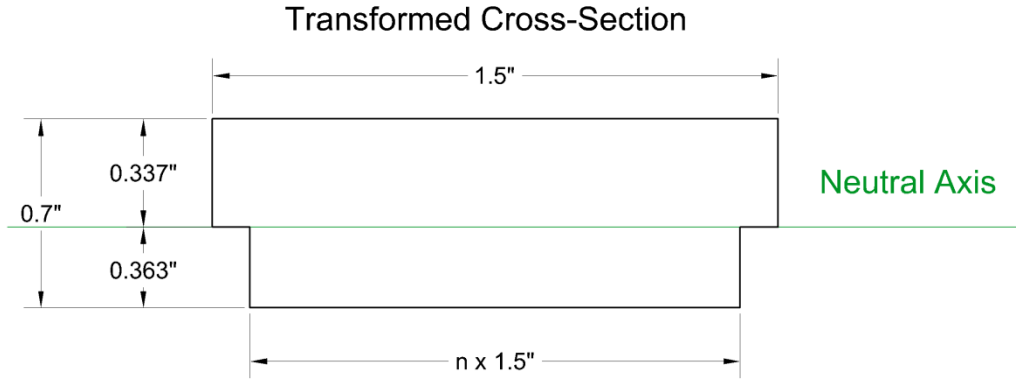


**Fig. A-1: epoxy section with stress and strain diagram**

As explained previously, the epoxy is weaker in tension compared to compression. Therefore, epoxy in tension is the first to fracture. From table 2-2, the epoxy in tension at ultimate strength can resist 6.04 ksi of tensile stress and will be strained to 0.0247 in/in at failure. Using the value for modular ratio shown in table 2-2 the transformed section for the epoxy is shown in



fig. A-2:



**Fig. A-2: transformed cross-section of the 0.7” deep epoxy**

Again for the new section the equilibrium in the longitudinal direction can be written from eqn. 2-3, where 6.974 ksi and 0.866 are substituted for “ $\sigma_{t\text{Trans}}$ ” and “ $n$ ” respectively.

$$\left(\frac{1}{2} * \sigma_c\right) * d_c * 1.5" = \left(\frac{1}{2} * 6.974\right) * d_t * 0.866 * 1.5"$$

$$\sigma_c * d_c = 6.974 * d_t * 0.866$$

$$\varepsilon_c * E_c * \frac{d_c}{d_t} = 6.04 * 0.866$$

From eqn. 2-2, substituting “ $\varepsilon_c/\varepsilon_t$ ” with “ $d_c/d_t$ ” we have:

$$\varepsilon_c * 281.7 * \frac{\varepsilon_c}{\varepsilon_t} = 6.974 * 0.866$$

$$\varepsilon_c^2 = \frac{6.974 * 0.866 * 0.0247}{281.7}$$

$$\varepsilon_c = 0.0230 \text{ in/in}$$

Using eqn. 2-2 “ $d_c$ ” yields 0.337”.

“ $\epsilon_c$ ” calculated here is very close to compression strain that was calculated for the 0.5” sample. This indicates that for any rectangular section for the section to be in equilibrium in longitudinal direction, the maximum stress and strain in tension and compression should be the same. The reason for this is the fact that the epoxy only follows linear stress and strain behavior until failure. Also, the location of the neutral axis adjusts so the compression and tension epoxy be in equilibrium. Yet, for the equilibrium to occur, the location of the neutral axis should be unique for any epoxy section of similar shape with different dimensions. For this reason, “ $d_c / d$ ” for any given rectangular section should be the same as the value determined for the 0.5” sample tested and analyzed in this document.

$$\frac{d_c}{d} = \left( \frac{0.241"}{0.5"} \right)_{for\ 0.5" epoxy} = \left( \frac{0.337"}{0.7"} \right)_{for\ 0.7" epoxy} = 48.1\% \quad (A-1)$$

Alternatively “ $d_t/d=51.9\%$ ” can be used to find “ $d_t$ ”. Deducting “ $d_c$ ” from the total depth of the sample, “ $d_t$ ” will yield 0.363”. Now the bending resistance of the section can be computed based on eqn. 2-9:

$$M - \left( \frac{1}{2} * \sigma_c \right) * d_c * 1.5 * \frac{2}{3} * d_c + \left( \frac{1}{2} * \sigma_t \right) * d_t * 1.5 * \frac{2}{3} * d_t = 0$$

$$M = \left( \frac{1}{2} * 6.49 \right) * 0.337 * 1.5 * \frac{2}{3} * 0.337 + \left( \frac{1}{2} * 6.04 \right) * 0.363 * 1.5 * \frac{2}{3} * 0.363$$

$$= 0.766 \text{ kip-in}$$

The deflection correspond to the maximum bending moment can be calculated based on eqn. 2-8. From fig. A-2 the transformed moment of inertia for the epoxy section is calculated as follows:

$$I_{Trans} = \frac{1}{3} * 1.5 * 0.337^3 + \frac{1}{3} * 0.866 * 1.5 * 0.363^3 = 0.03985 \text{ in}^4$$

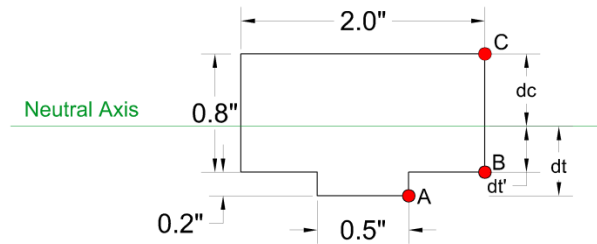
$$\delta = \frac{P * L^3}{48 * E_c * I_{Trans}}$$

$$\delta = \frac{\left(0.766 * \frac{4}{10}\right) * 10^3}{48 * 281.7 * 0.03985} = 0.569 \text{ in}$$

These values are plotted on fig. 2-12 in the document. This approach can be used for any rectangular section.

## A.2 Estimating flexural capacity for nonrectangular epoxy sections

For nonrectangular cross-sections, the same concept can be used to estimate the flexural strength of epoxy with a slight change. Fig. A-3 shows a section similar to the effective section of the epoxy before cracking with random dimensions.



**Fig. A-3 nonrectangular epoxy cross-section**

For nonrectangular sections, the distance of the neutral axis to the top or bottom of the section is not proportional the value determined in the previous section. To locate the neutral axis, again the stress and strain at the bottom fiber should be set to 6.04 ksi and 0.0247 in/in respectively. Now through, trial and error, the neutral axis is to be determined so the section is in equilibrium in the longitudinal direction of the sample. Since the change in strain is linear over the depth of the epoxy profile, for different “ $d_c$ ” or “ $d_t$ ”, “ $\epsilon_c$ ” could be determined based on strain compatibility (eqn. 2-2). Having the strain at the extreme compression fiber, the stress can by

calculated by multiplying the strain by the compression modulus of elasticity. Through iteration, the location of neutral axis can be found when the section is in equilibrium. For the section shown on fig. A-3, after few iteration we have:

Assume  $d_t = 0.585''$

Therefore  $d_c = 1.0'' - 0.585'' = 0.415''$

Find stress at “B” and “C” (eqn. 2-2):

$$\frac{\varepsilon_t'}{\varepsilon_t} = \frac{d_t'}{d_t} \rightarrow \varepsilon_t' = \frac{0.0247 * 0.385''}{0.585''} = 0.01625$$

$$\sigma_t' = E_t * \varepsilon_t' = 244.36ksi * 0.01625 = 3.972ksi$$

$$\frac{\varepsilon_c}{\varepsilon_t} = \frac{d_c}{d_t} \rightarrow \varepsilon_c = \frac{0.0247 * 0.415''}{0.585''} = 0.0175$$

$$\sigma_c = E_c * \varepsilon_c = 281.7ksi * 0.0175 = 4.93ksi$$

Now the stress is determined at all points the equilibrium on the cross section can be written as:

$$\begin{aligned} & \overbrace{\left[ \left( \frac{\sigma_c}{2} \right) * d_c * 2'' \right]}^{F_c} - \overbrace{\left[ \frac{\sigma_t + \sigma_t'}{2} * (d_t - d_t') * 0.5'' \right] - \left[ \frac{\sigma_t'}{2} * d_t' * 2'' \right]}^{F_t} = 0 \\ & \left[ \left( \frac{4.93ksi}{2} \right) * 0.415'' * 2'' \right] - \left[ \frac{6.04ksi + 3.972ksi}{2} * (0.585'' - 0.385'') * 0.5'' \right] \\ & - \left[ \frac{3.972ksi}{2} * 0.385'' * 2'' \right] = 0 \\ & F_c - F_t = 2.045kip - 2.030kips = 0.015kips \approx 0 \end{aligned}$$

This means that the assumed location of the neutral axis is correct and the section is in equilibrium. Now that the neutral axis is located the flexural strength of the section could be found as:

$$M = F_c * \frac{2}{3} d_c + F_t' * \frac{2}{3} d_t' + F_t * \frac{d_t + d_t'}{2}$$

$$2.045 * \frac{2}{3} * 0.415" + 1.53kip * \frac{2}{3} 0.385" + 0.5kip * 0.485" = 1.2 \text{ kip-in}$$

Same approach could be used for any given section geometry.

## VITA

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